INL/MIS-20-59777-Revision-0

FPOG Stakeholders Engagement Meeting, September 10, 2020

Richard D Boardman, Cristian Rabiti, Tyler L Westover, Kurt G Vedros, Kenneth D Thomas, Jack Cadogan

September 2020

Idaho National Laboratory

The INL is a U.S. Department of Energy National Laboratory
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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Bruce

LWRS Flexible Plant Operation and Generation Utility Stakeholder Meeting

- Welcome (5 min)
  - Alison Hahn- US Department of Energy, Office of Nuclear Energy - LWRS Federal Program Manager
  - Bruce Hallbert- National Technical Director, LWRS Program
  - Jack Cadogan- Meeting Discussion Facilitator
  - Ken Thomas- Pathway Advisor
- Nuclear Power Plants Market Perspective (20 min)
  - Jack Cadogan, Meeting Agenda, Role of Nuclear Power Plants in Electricity Markets
  - Ken Thomas, Function of Nuclear Power Plant / Opportunities and Challenges of FPOG
  - Discussion with Stakeholders
- Panel: R&D Progress and Accomplishments (60 minutes)
  - Summary of TEAs, Richard Boardman
  - Summary of FPOG tools and plans, Cristian Rabiti
  - Summary of thermal energy extraction modeling, and testing, Tyler Westover
  - Hydrogen plant safety analysis, Kurt Vedros
  - Summary of demonstration project objectives and scope, Richard Boardman
  - Q&A
- Round-the-table input and comments (45 minutes)
  - Summary of owner interests and questions
  - Recommendations for timing and approaches to engage technology providers and industrial partners
- Next Steps (15 minutes)
  - Next meeting time, format, and participation
  - Research Leads follow-up with individual stakeholders
  - Arranging meetings with technology and industrial stakeholders
  - Other…
- Summary and adjourn (5 minutes)

Jack

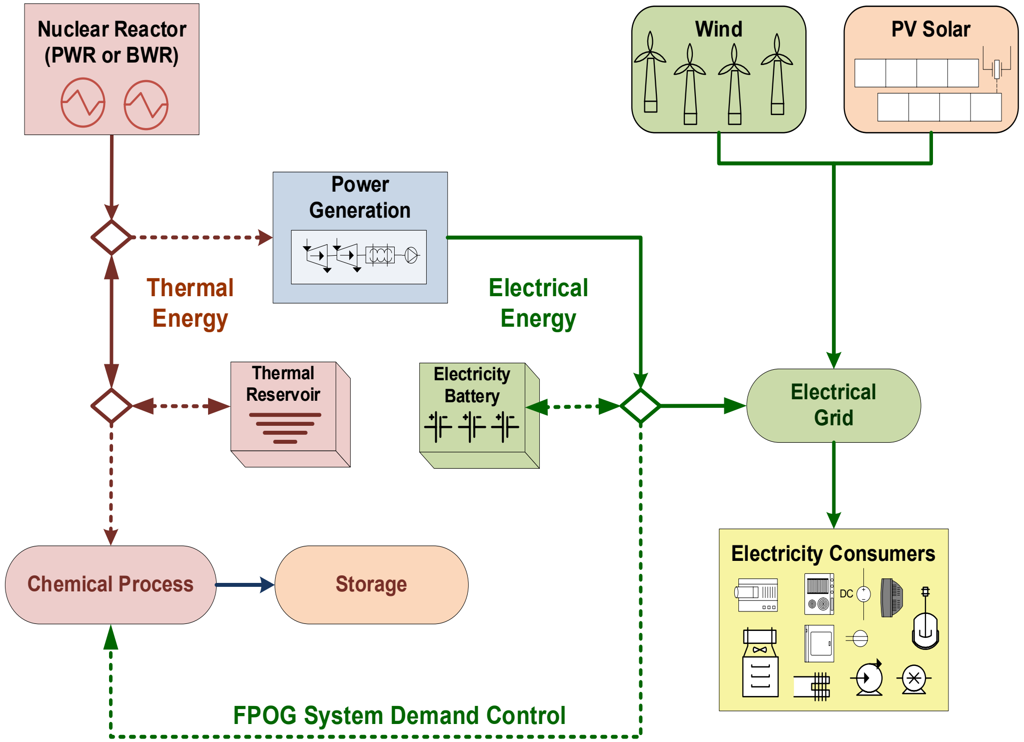
FPOG Key Stakeholder Meeting

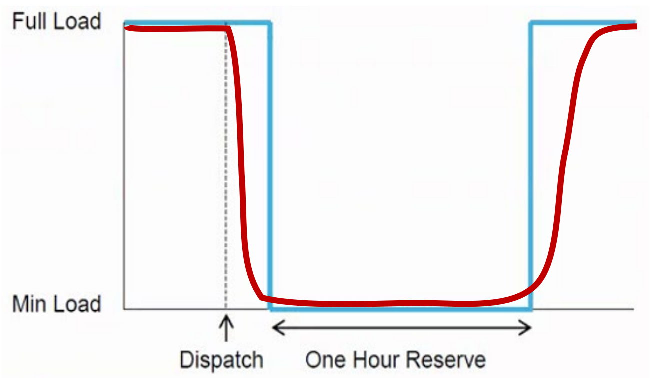
- Facilitators: Jack Cadogan and Ken Thomas
- *Goals:*
  - Summarize the goals and current activities of the LWRS Flexible Plant Operations and Generation Pathway
  - Provide an opportunity to discuss activities, plans, and progress of ongoing and planned R&D
  - Identify interests for periodic stakeholder engagement and discuss future engagement options.
- *FPOG Key Stakeholder Engagement Group:*
  - Owners/Operators of nuclear power plants interested in learning or participating in research, development, and demonstration activities to increase plant revenue through flexible plant operations
  - Vendors and suppliers of candidate systems and needed technologies to enable development and demonstration activities and their commercial deployment
  - The Electric Power Research Institute and other research organizations that enable the development of key capabilities needed to successfully develop and deploy these systems
  - Nuclear Energy Institute, Nuclear Regulatory Commission, and other stakeholders
- *Key Activities:*
  - Review LWRS Technical Program Plan for FPOG
  - Discuss and recommend FPOG R&D activities and priorities
  - Recommend timing and approach to engage technology developer and industry stakeholders

Ken

Nuclear Plant Operating Options

- Flexible Power Operations (FPO)
  - EPRI Studies and Guidance
  - Eight areas of potential impact
- Dedicated energy supplier to an industrial process
  - Off grid
  - Steam and or electricity supply
- Hybrid Operations
  - Dispatch electricity between grid and industry user
  - Dispatch electricity and steam
  - Provide grid services
    - supply and demand response
    - grid regulation





Jack

Panel: FPOG R&D Activities

- Summary of TEAs
- Summary of FPOG tools and plans
- Summary of thermal energy extraction modeling, and testing
- Hydrogen plant safety analysis
- Summary of demonstration project objectives and scope
- Q&A

Richard

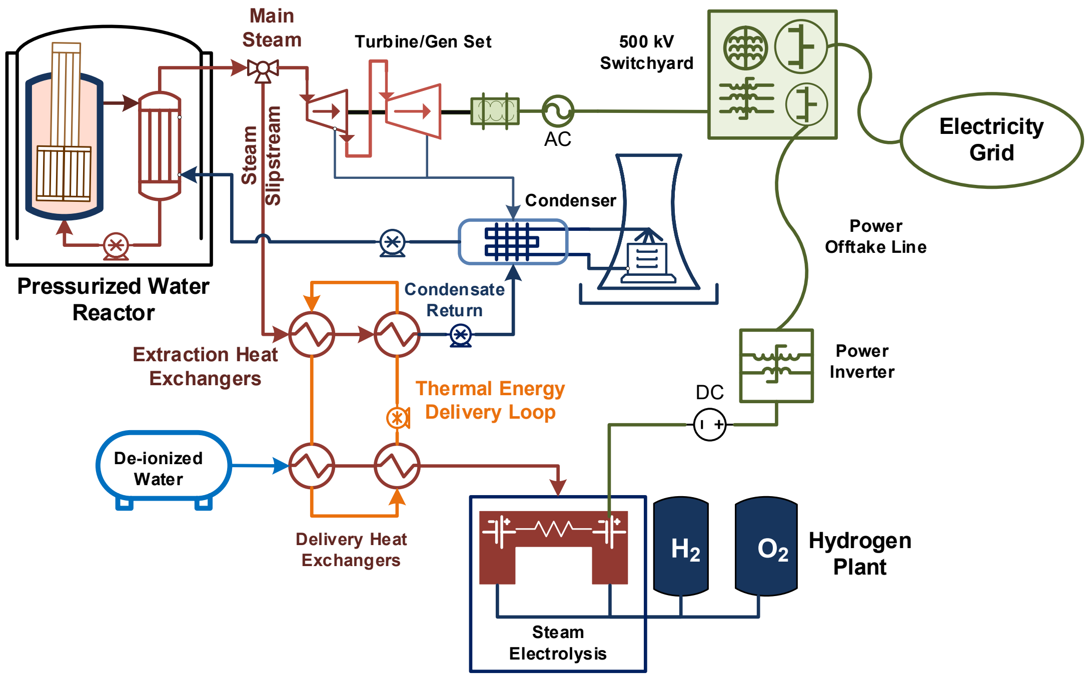
Goals and Objectives of FPOG Pathway

- The purpose of this pathway is to diversify and increase the revenue of light water reactors in the United States
- The main goal is to reduce the technical and economic risks of commercial deployment of these systems and to help LWR owners implement and test the leading options.
- Three Activity Areas

I. **Energy Dispatch:** The purpose of this activity is to develop efficient electricity and thermal energy delivery systems and conduct reactor operator human factors and control systems research that is needed to dynamically extract and deliver thermal energy from a nuclear power plant for use by an industrial process.

II. **Design and Economics:** The purpose of this activity is to complete technical and economic assessments to evaluate market opportunities for LWRs to supply electricity and steam or heat to produce non-electricity products.

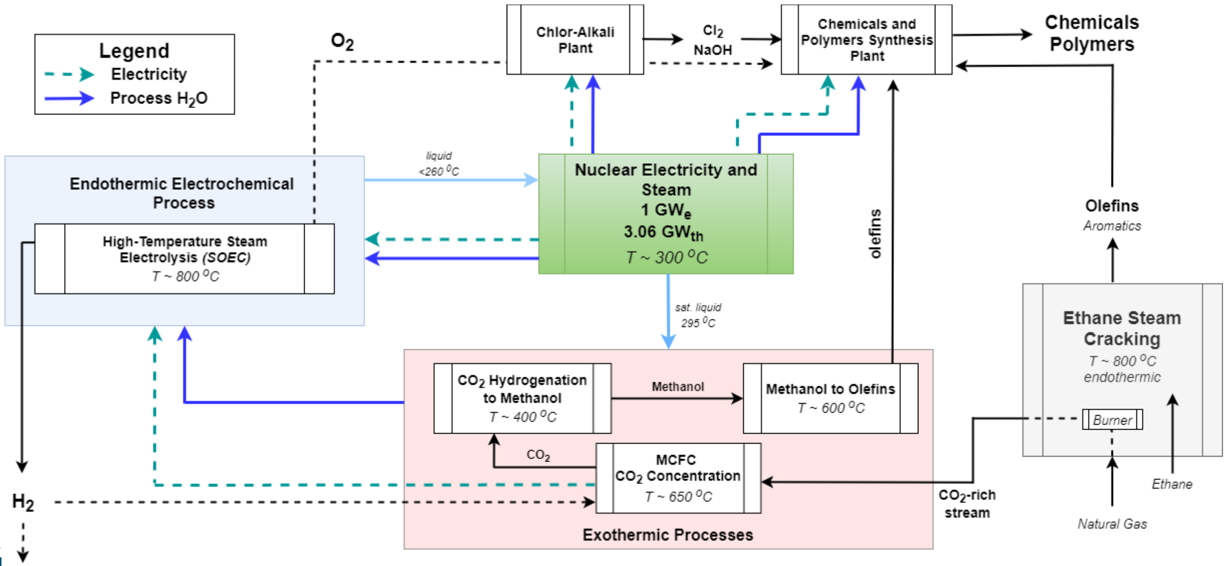
III. **Safety Assessments:** The goal of this effort is to ensure the FPOG operations remain within the operating basis of LWRs or to otherwise inform plant owners on license modifications for relatively large percentages of LWR thermal energy delivery to an industrial user.

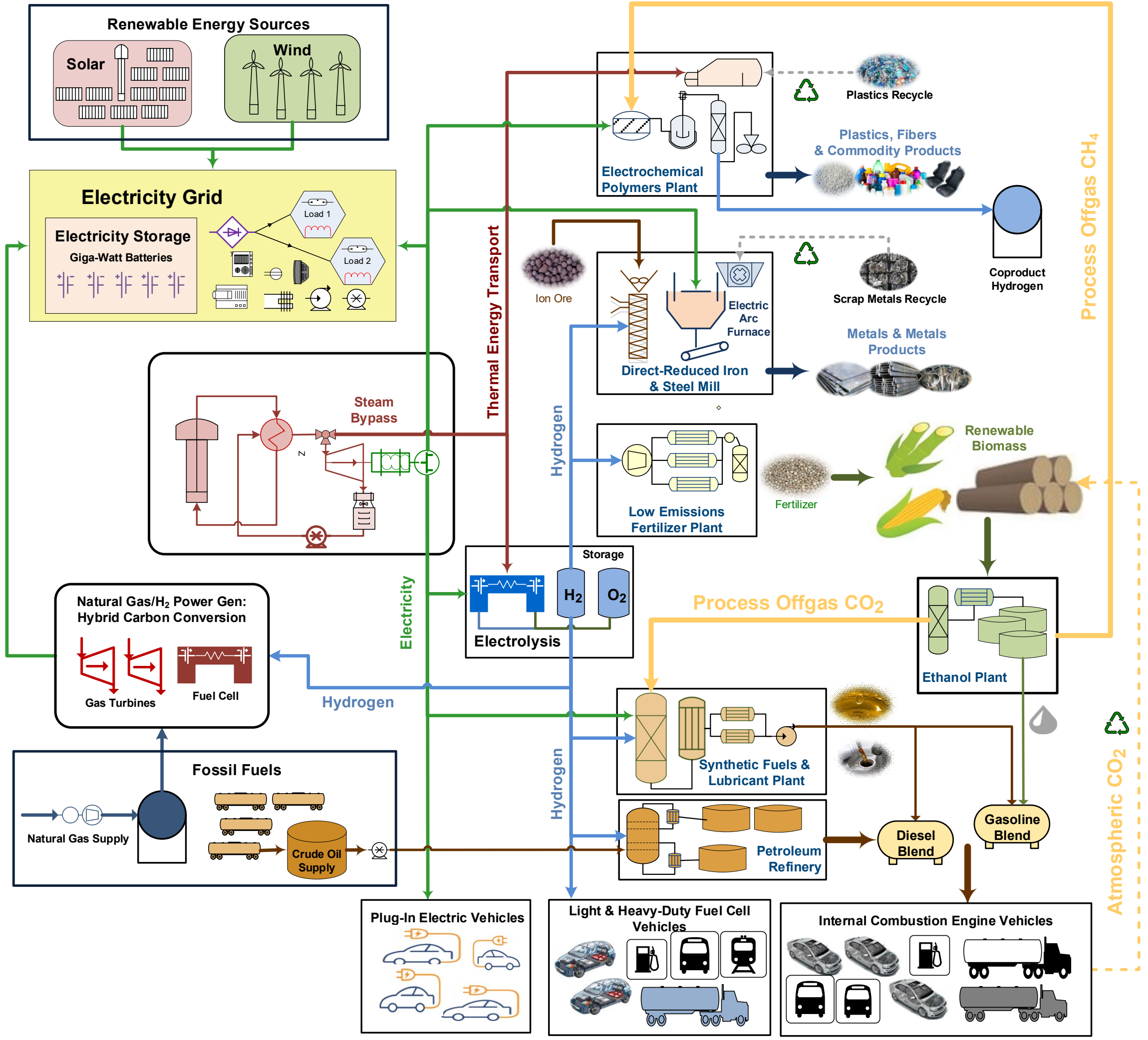


Richard

Technoeconomic Assessments

- ❑ Hydrogen generation and hydrogen markets
- ❑ Polymers & plastics from natural gas
- ❑ Pure thermal markets
- ❑ Synthetic fuels
- ❑ Energy Storage

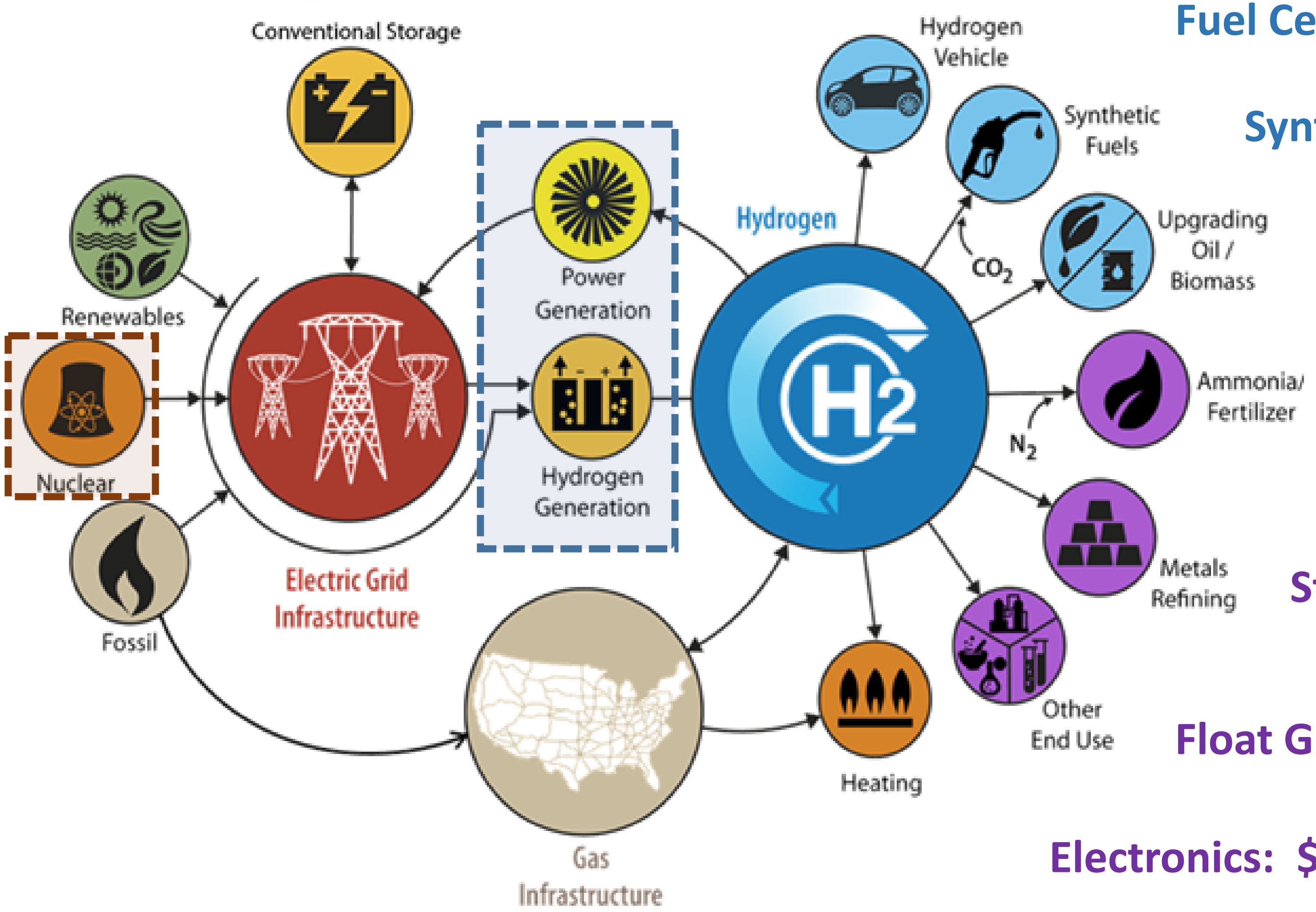




Specific Industrial Park Concept using nuclear heat and electricity to produce chemicals and polymers with minimal CO_2 emissions

Richard

Hydrogen Market Disruption



Fuel Cell Vehicles: \$1.50 – 3.00 / kg-H_2

Synthetic Fuels: \$1.50 – 1.75 / kg-H_2

Refining: \$1.25 – 2.00 / kg-H_2

Ammonia: \$1.50 – 1.75 / kg-H_2

Steel: \$1.00 – 1.25 / kg-H_2

Float Glass: \$1.25 – 1.75 / kg-H_2

Electronics: \$3.00 – 5.00 / kg-H_2

Clean H_2 value of CO_2 avoided: \$10/tonne-CO2 avoided » -\$0.10 / kg H_2

Cristian

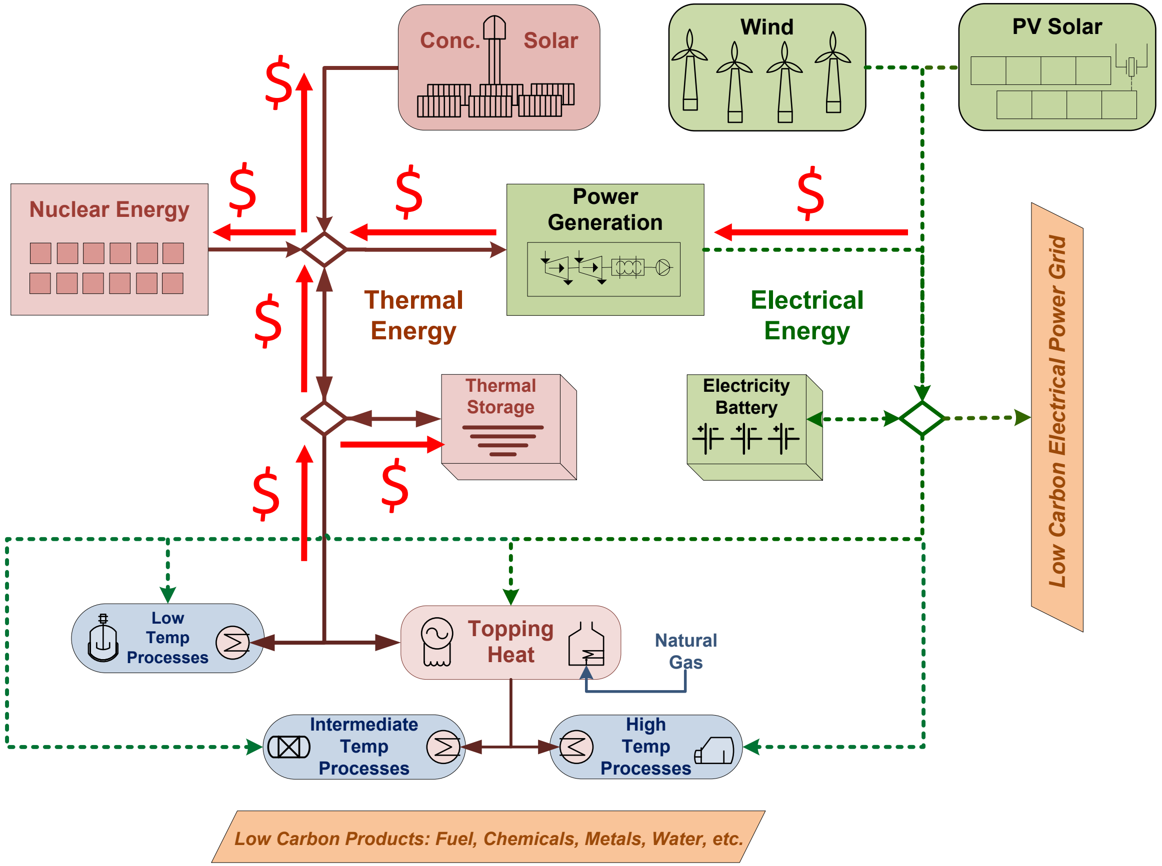
FPOG System Modeling end Optimization

HERON

- Goals
  - Deliver the capability to perform technoeconomic assessment of FPOG systems: HERON
    - NPV, IRR for long term projects

- Challenges
  - Very long time scales
  - Revenues depends on market interaction at short and long term
  - multiple market and revenue streams
  - Probabilistic problem

- Approaches
  - Focus on LWRS relevant problems
  - Leverages synergism with other programs and laboratories
    - CTD-IES
    - NREL
    - NTEL



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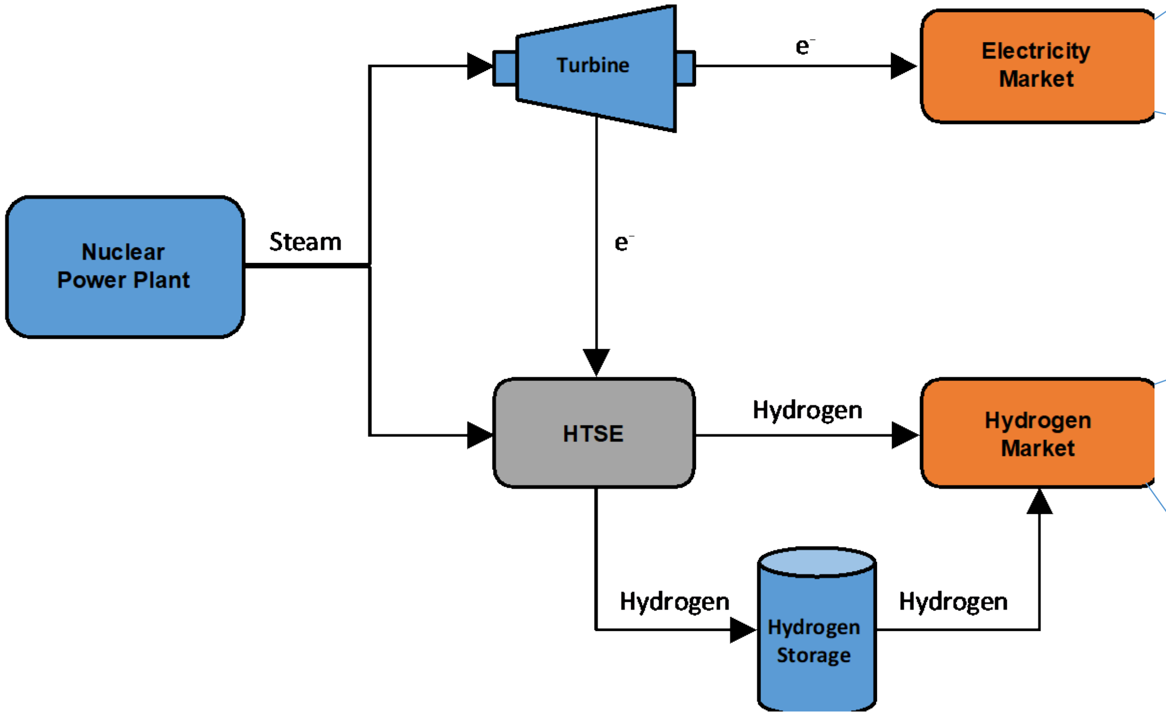
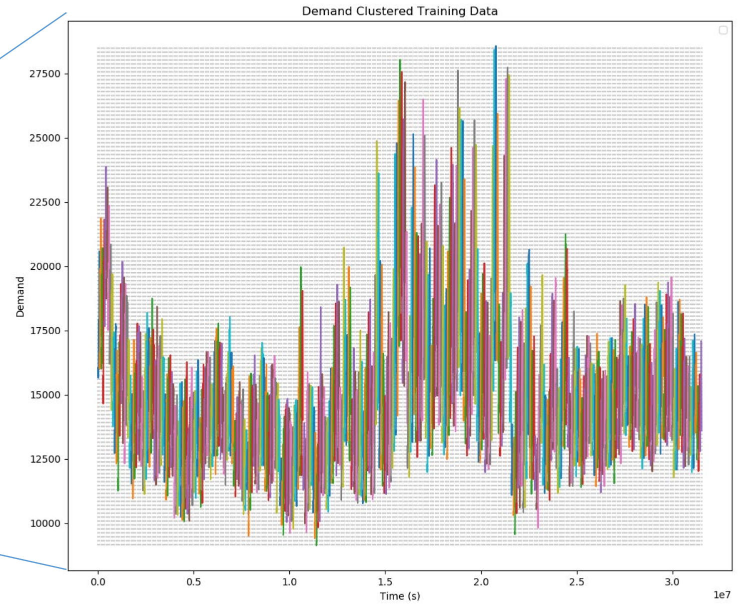
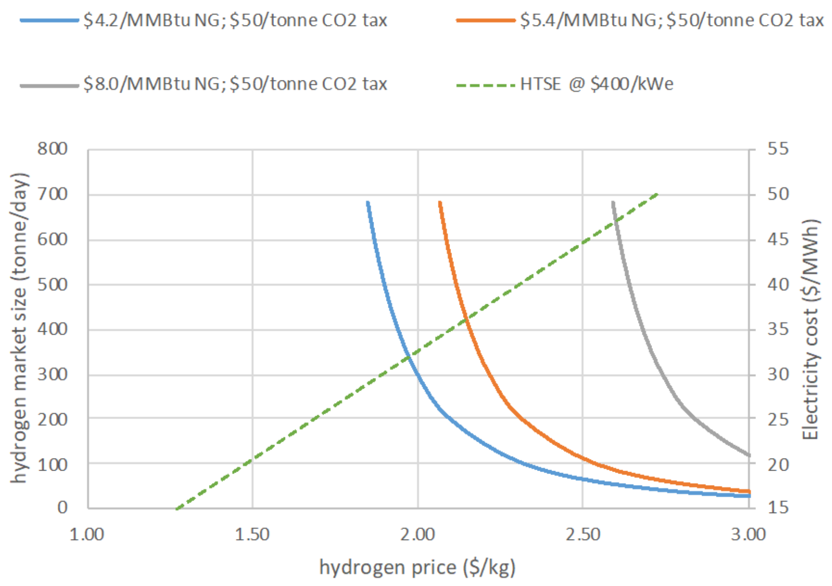
Demo Case





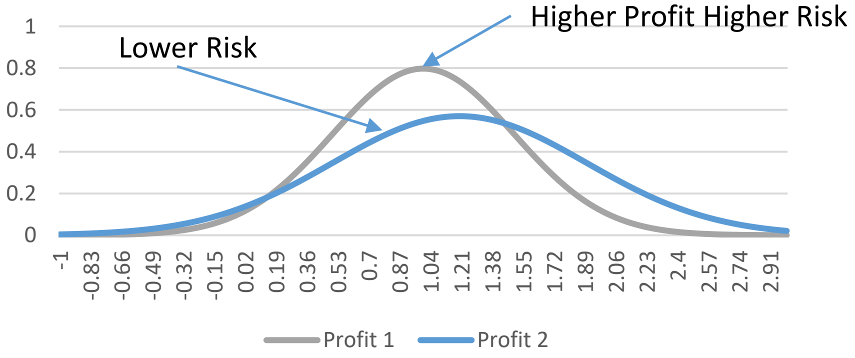


Cristian

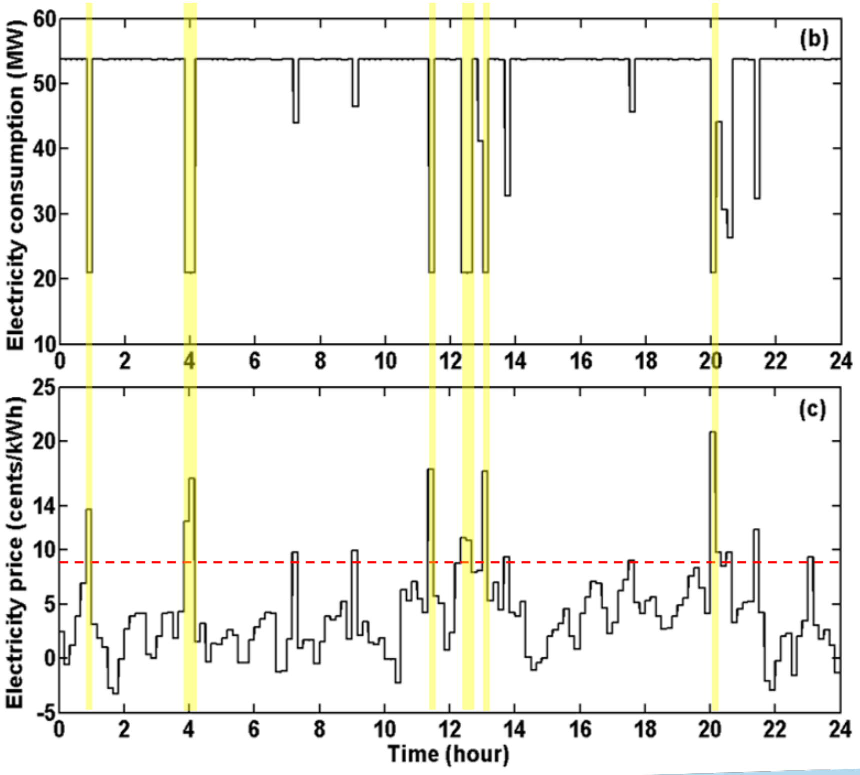
Challenges

- Very long time scales
  - NPP life time extend for 60 to 80 years, many power plants have in excess of 20 years of residual lifetime
  - Chemical plants life time is at least in several tens of years
- multiple market and revenue streams
  - Heat market
  - Hydrogen
  - …

Probabilistic revenue streams



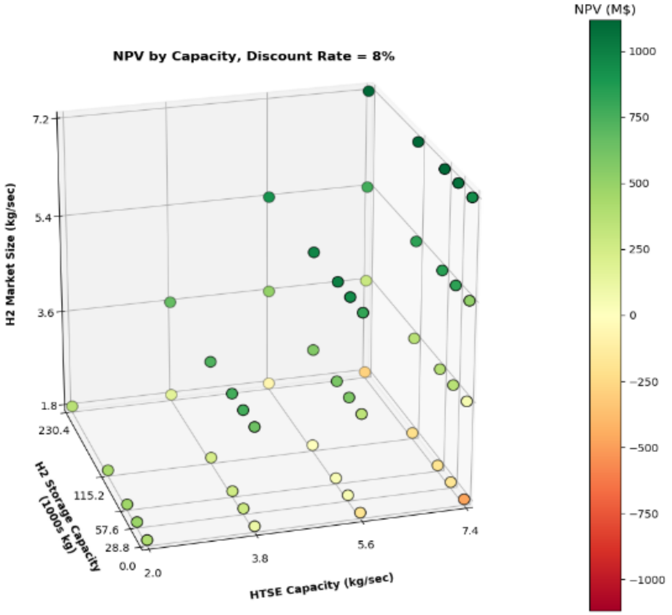
- Revenues depends on market interaction at short and long term
  - Day head market
  - Imbalance market
  - Ancillary services

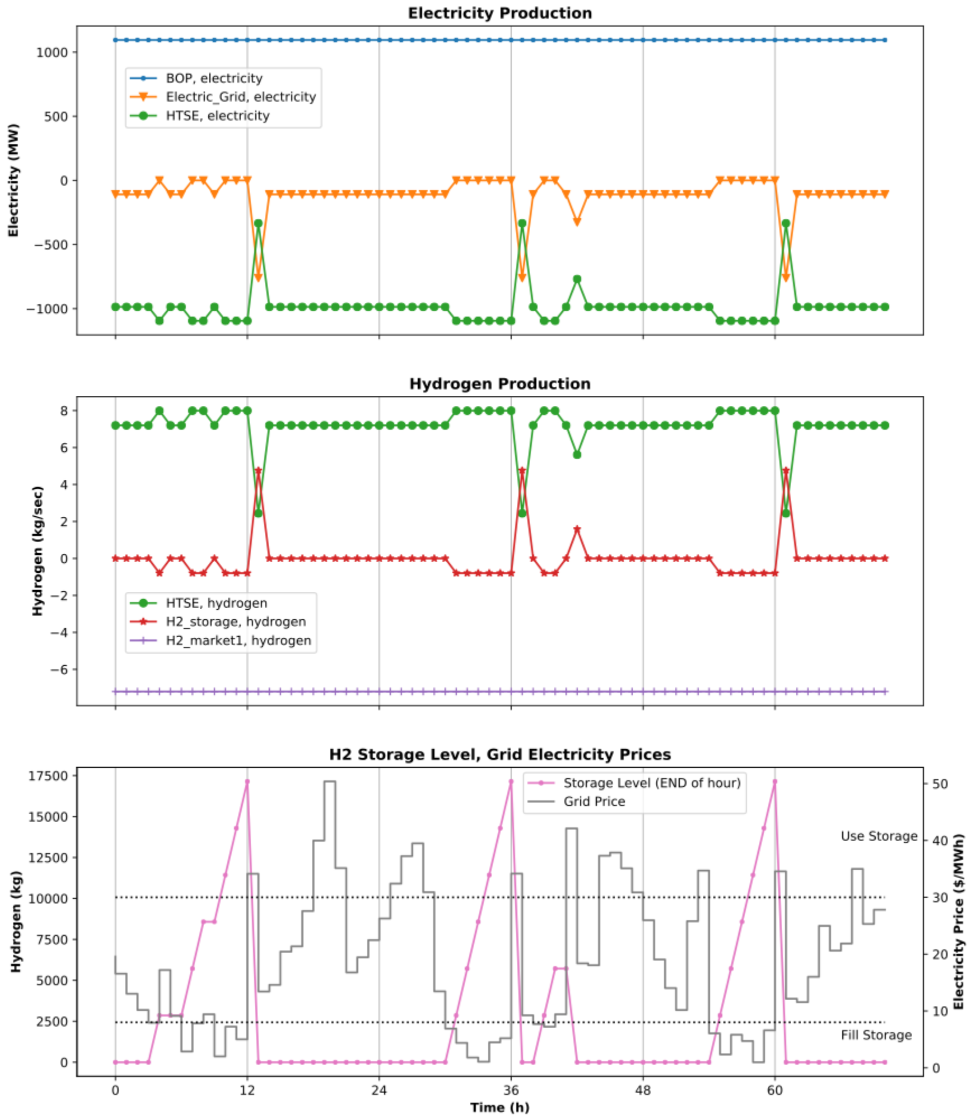


Cristian

The Exelon Case

- NPV optimization
- Optimization parameters
  - Buy low
  - Sell high
  - Capacity H2 production
  - Storage size
- Markets:
  - Day head
  - Hydrogen (demand curve)





ReEDS (NREL): portfolio Evolution

2026 → PLEXOS

2030 → PLEXOS

2034 → PLEXOS

2038 → PLEXOS

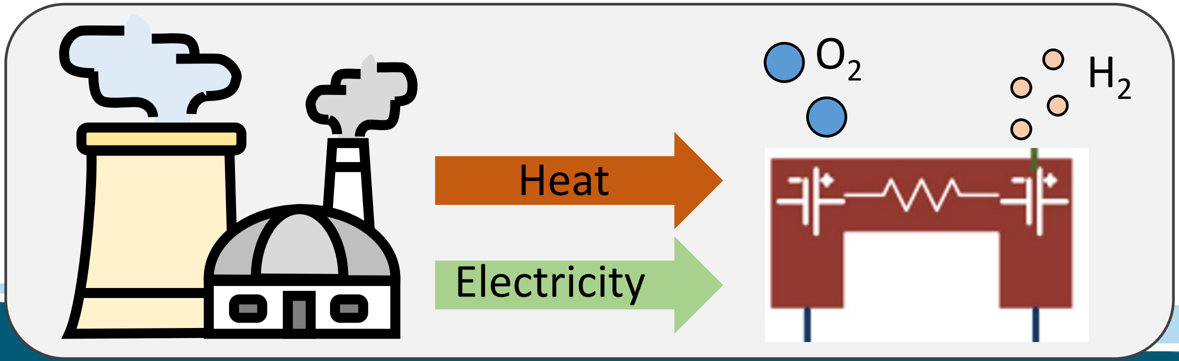
2042 → PLEXOS

RAVEN/HERON

Tyler

Coupled Thermal & Electric Power Dispatch from NPPs

- **High Level Approach**
  1. Full-scope, high fidelity NPP simulators with coupled thermal and electric power dispatch with human-in-the-loop operations
     - Pro #1: Realistic simulations that support probabilistic risk assessments (PRAs), other licensing issues, and technoeconomic assessments;
     - Pro #2: Can capture realistic coupling between NPP and specific industry power user
     - Con #1: Highly complex simulations are only as good as the underlying assumptions;
     - Con #2: Simulations cannot qualify hardware and require validation
  2. Limited-scope, pilot-scale simulators with coupled thermal and electric power dispatch with human- and hardware-in-the-loop operations
     - Pro #1: Hardware-in-the-loop tests probe vital interactions between systems that can be missed in purely digital simulations;
     - Pro #2: Can qualify hardware and validate high fidelity models;
     - Pro #3: Combines human and hardware factors – essential for coupling to new technologies, such as advanced low or high temperature electrolysis
     - Con #1: Demonstration scale may not match commercial scale – need scaling functions;
     - Con #2: Hardware requires substantial capital and time investments



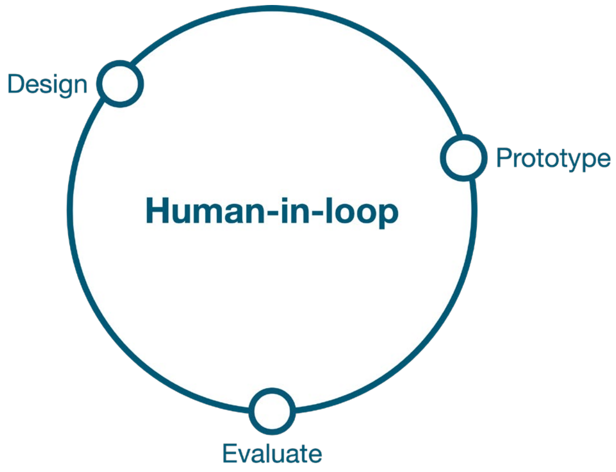
Tyler

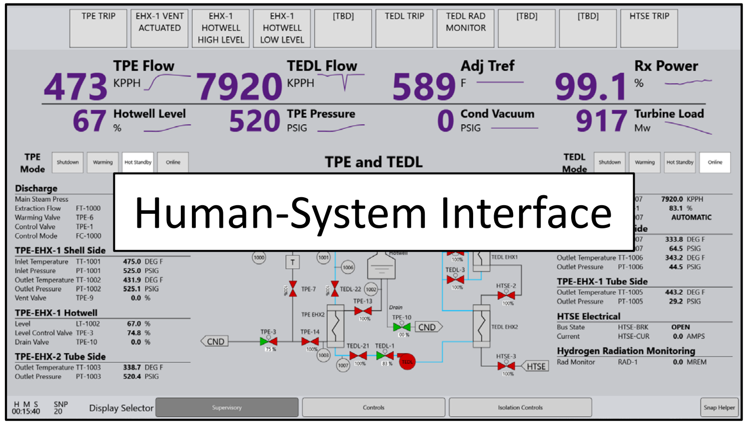
Concept of Operations

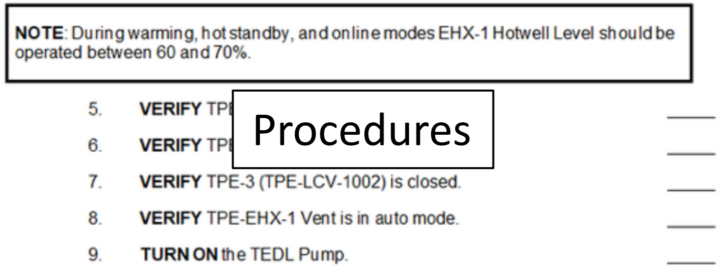
Develop, demonstrate and evaluate Thermal Power Dispatch

- Concept of operations to couple a nuclear power plant with a hydrogen production plant
    - HSI and Procedures

Focuses on an iterative operator-centered design process



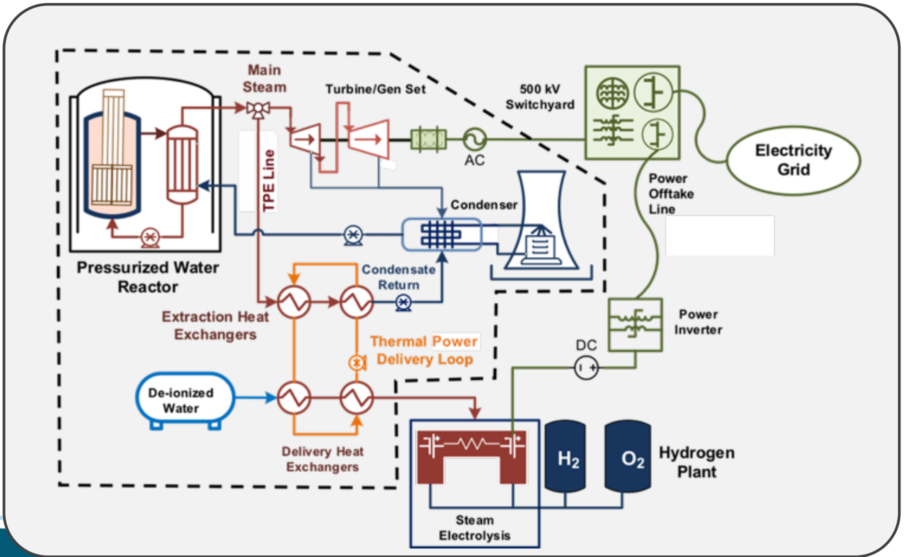


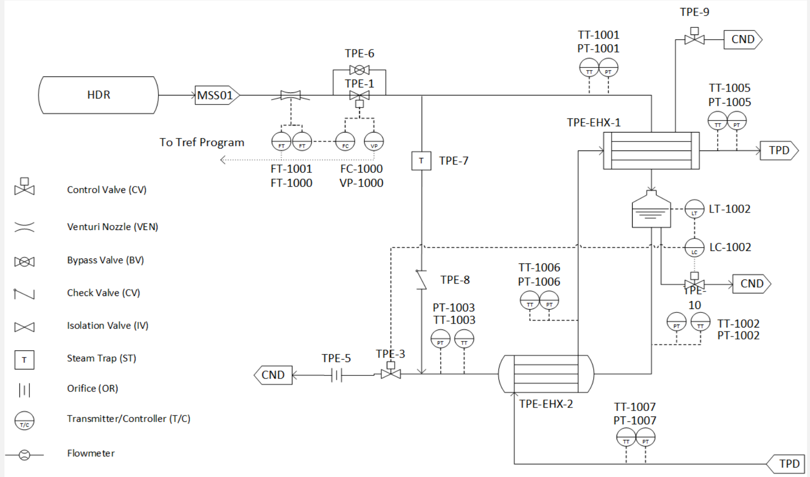


Tyler

Coupled Thermal & Electric Power Dispatch from NPPs

- **Accomplishments**
  1. Developed Full-scope, High Fidelity Thermal Power Dispatch Generic PWR Simulator (electric power dispatch is highly simplified)
     - Based on GSE ® GPWR simulator
  2. Developed prototype Human/System Interface (HSI) and generic operating procedures for integrated GPWR/hydrogen generation plant system
  3. Performed human-in-the-loop tests with Thermal Power Dispatch GPWR using operating procedures

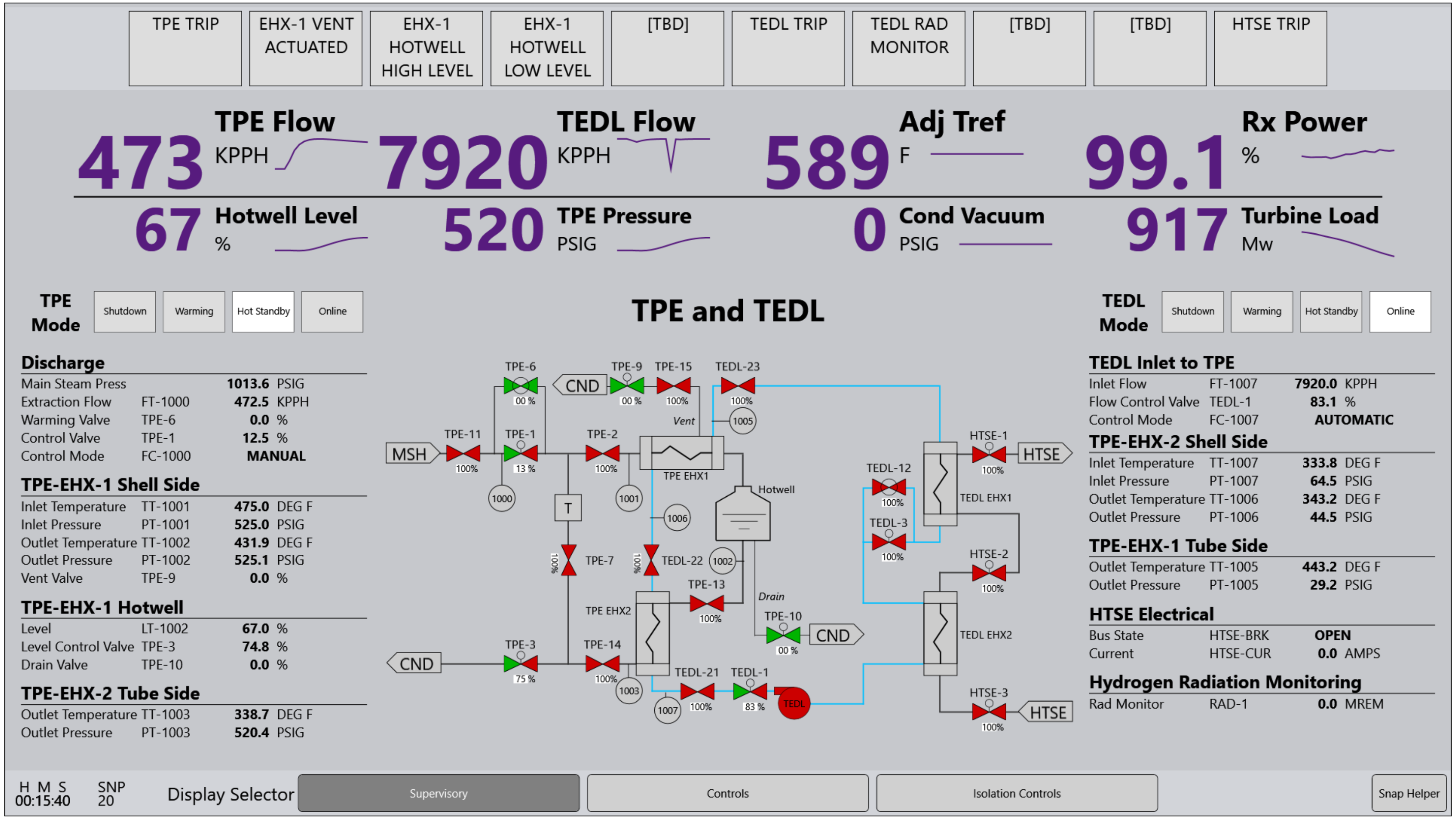




Piping & instrumentation diagram (P&ID) for thermal power extraction loop

Tyler

Accomplishment #2: Prototype Human System Interface Human Factors



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Tyler

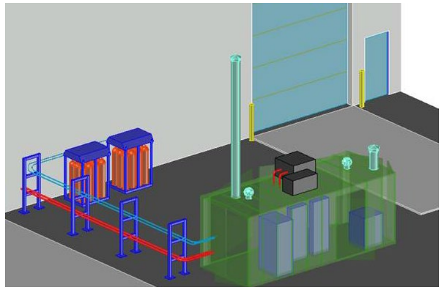
Accomplishment #3:
Human-in-the-loop Tests with Thermal Power Dispatch GPWR

- **Four operators (40 years in nuclear with 18.5 years as operators)**
  - 2 Harris; 2 EPRI*
- **Remote Usability Format**
  - Web meeting platform with screen control
  - Static “snapshots” or snaps of real simulator data – Generic PWR Model
- **Four basic operating scenarios**
  1. Shutdown to Hot Standby
  2. Hot Standby to Online
  3. Online to Hot Standby
  4. Hot Standby to Shutdown
- **Findings and Issues**
  - Approach was validated - operators were able to execute the procedures and were comfortable with the system
  - Operators provided comments to improve the operating procedures and HSI
  - Need more detailed model of coupling to industrial user for fully realistic simulations and testing.
  - Detailed models need to come from pilot-scale hardware-in-the-loop tests.

Tyler

Future Work

- **Human, and component tests with limited-scope, pilot-scale coupled thermal and electric power dispatch simulators**
  - Couple a 150+kW HTE system with Thermal Energy Distribution System (TEDS) at INL for human- and hardware-in-the-loop tests
  - Used to validate simulator predictions and hardware performance
  - Used to validate simulator predictions and hardware performance



150-250 kW HTE System

Grid-in-the-Loop

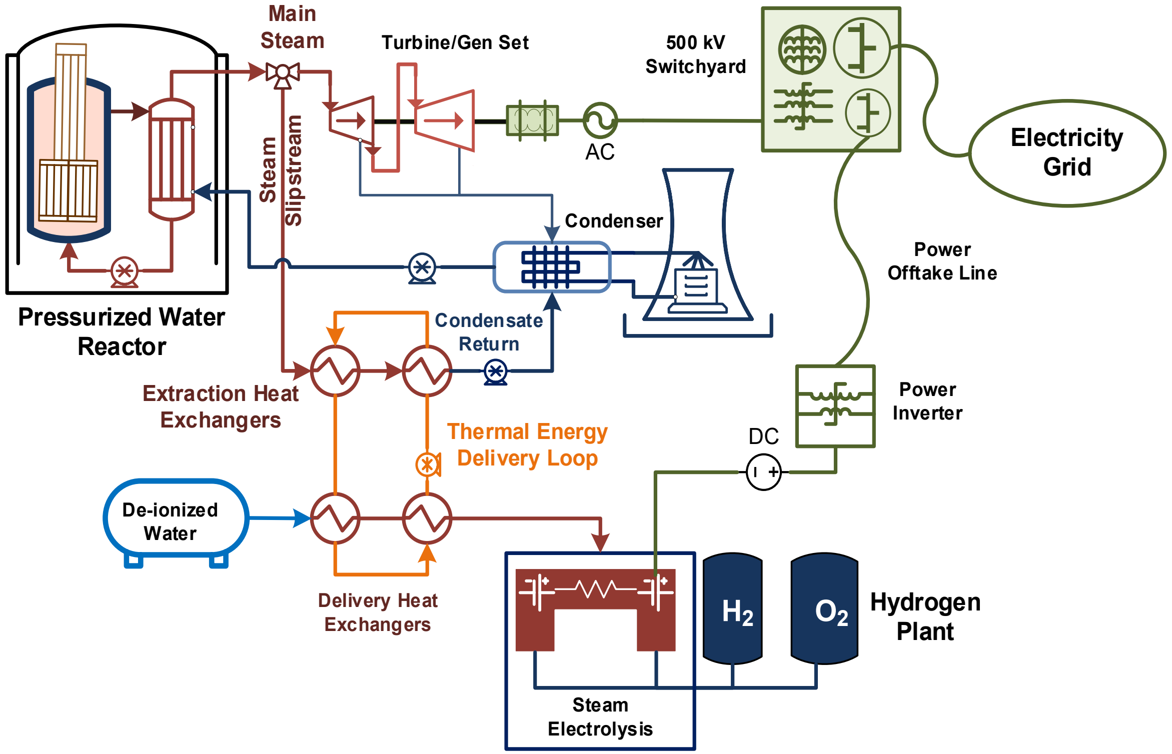
Thermal energy distribution

Human-in-the-Loop

Kurt

Evaluation of Safety Hazards and Licensing Considerations

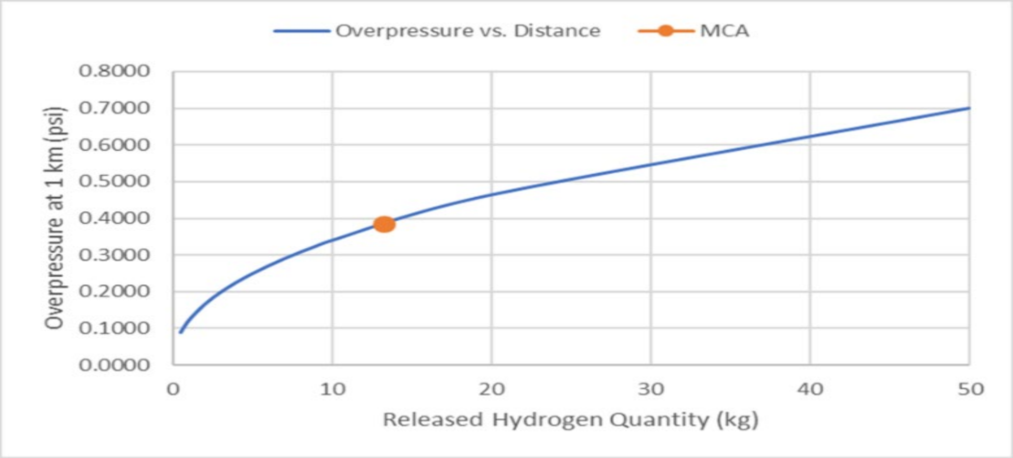
- **Licensing Pathways**
  - 10 CFR 50.59
  - RG 1.174
- **Probabilistic Risk Assessment**
  - Hazard analysis of generic PWR and BWR
    - Addition of Heat Extraction System
    - H2 High Temperature Electrolysis Facility
  - Identification of affected Licensing Basis Events
  - Quantification of the effects on LBE initiators
  - Quantification of the effects on CDF and LERF

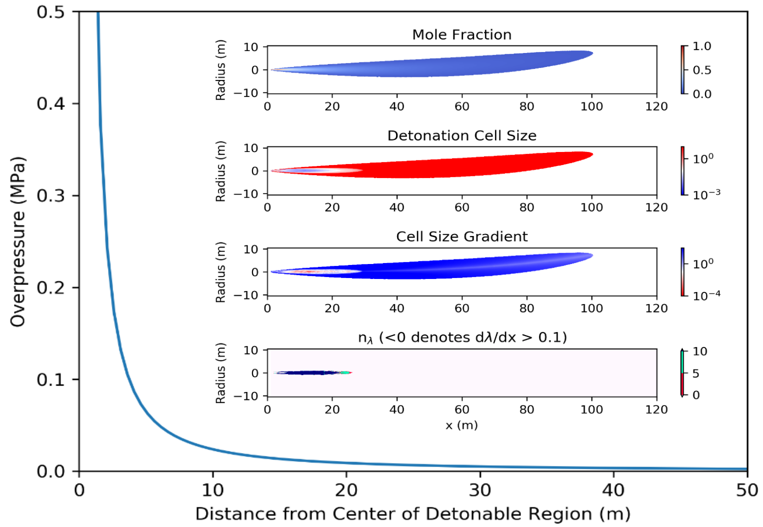


Kurt

Evaluation of Safety Hazards and Licensing Considerations

- **Hazards Identified**
  - **Internal to NPP**
    - **Steam line break in Heat Extraction System**
    - **LOOP frequency increase from HTEF accident**
  - **External to NPP**
    - **HTEF hydrogen leak**
    - **HTEF hydrogen detonation**
- **PRA Effects on Mitigation**
  - Unisolated large steam leak scenario

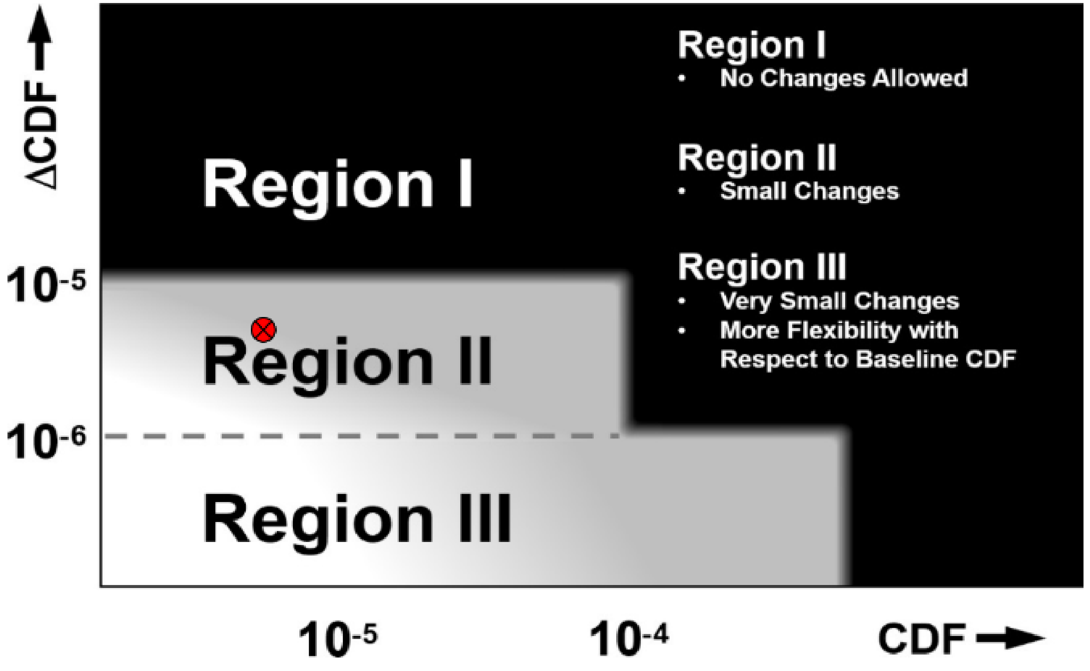




Kurt

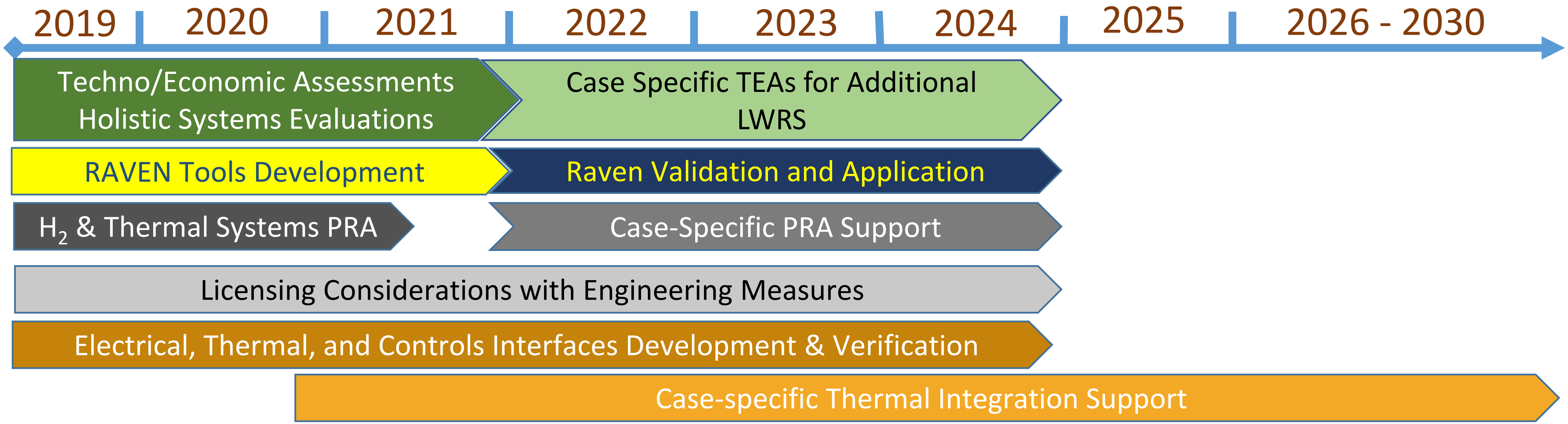
Evaluation of Safety Hazards and Licensing Considerations

- **Probabilistic Risk Assessment Results (Preliminary)**
  - Licensing Basis Events
    - Initiating event frequencies within the 10 CFR 50.59 criteria @ 1km separation distance
    - CDF and LERF well within Region II of RG 1.174 criteria
  - Sensitivity Studies
    - Separation distance
    - Number of HES isolation valves
    - Steam versus heating oil

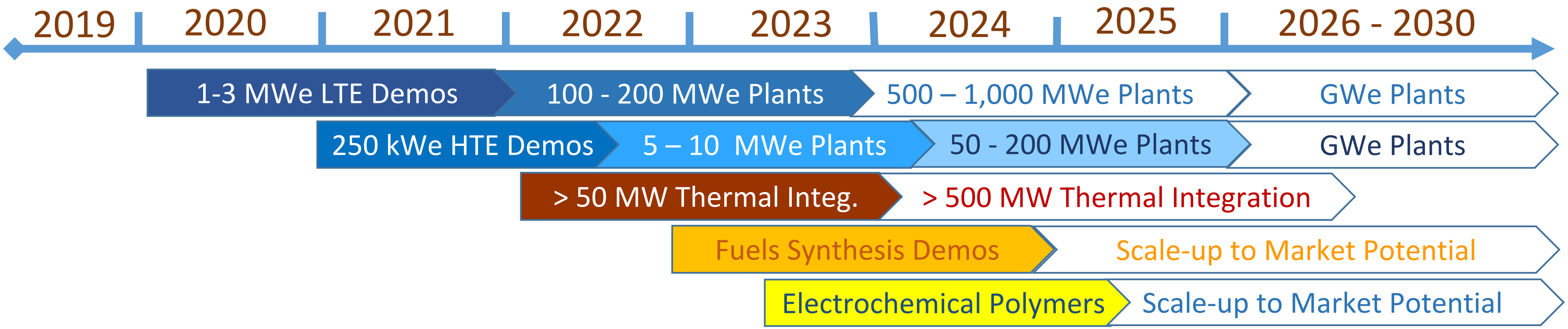


Richard

FPOG Pathway Activity Schedule



Demonstration Project Schedule



LWR-H_2 Demonstration Projects: Exelon, USA

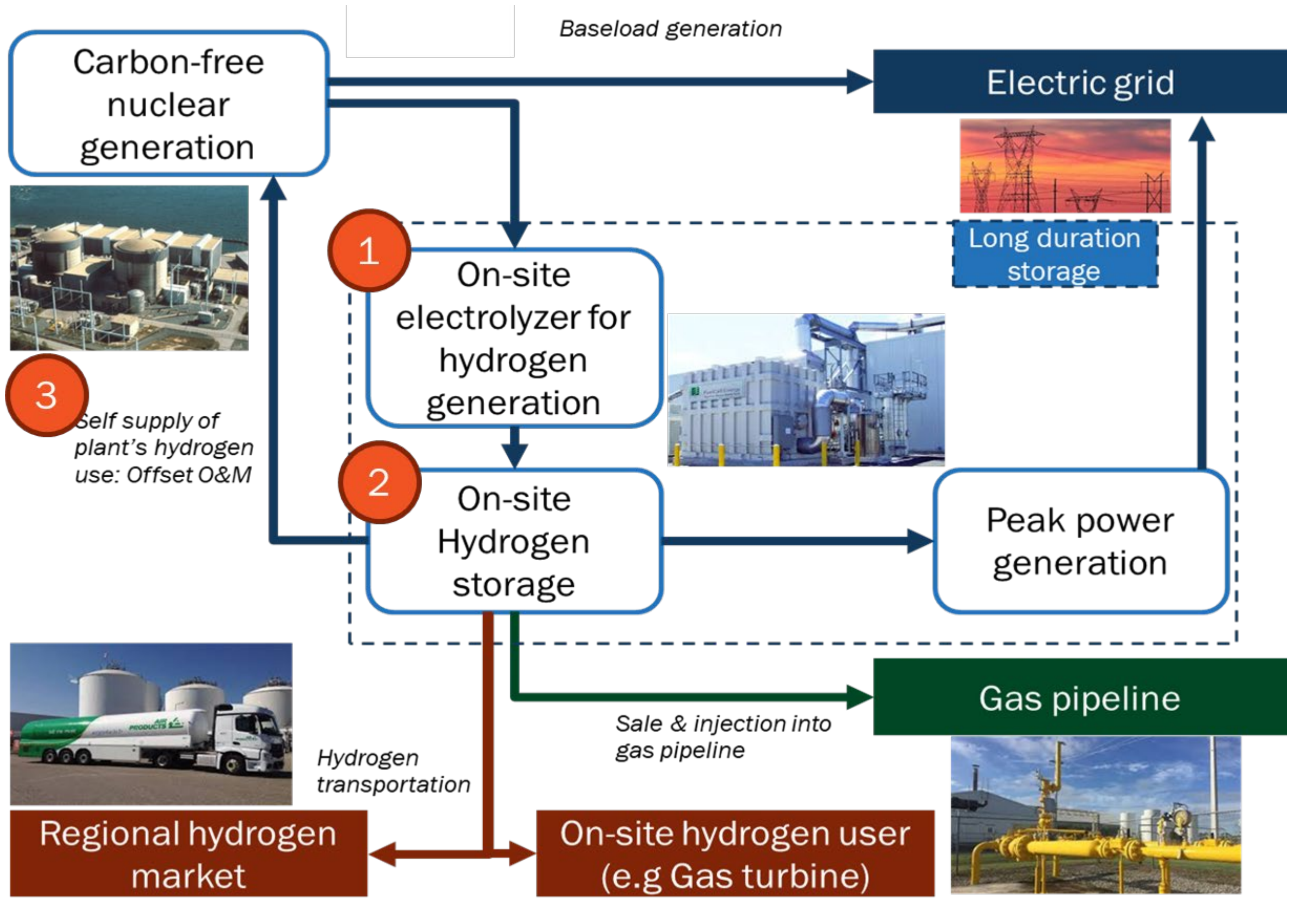
Exelon

Partners: Nel Hydrogen, ANL, INL, NREL (via DOE)

Analysis Report: Evaluation of Hydrogen Production for a Light Water Reactor in the Midwest

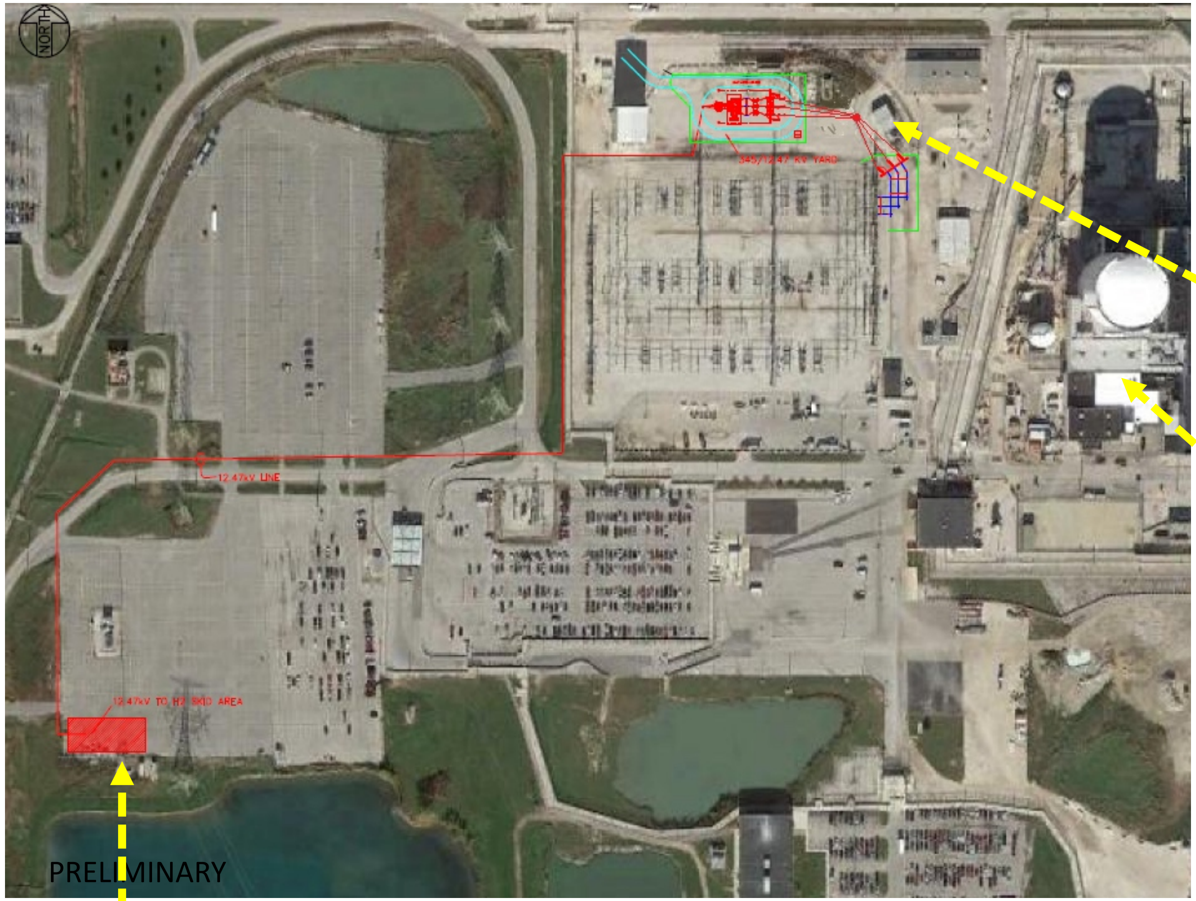
Purpose:

- Demonstrate hydrogen production using direct electrical power offtake from a nuclear power plant and acquaint plant operators with methods and controls for scaling up to large commercial plants.
- Evaluate power offtake dynamics and inverter control response to provide grid contingency, ramping reserves, and volt/reactive control reserve.
- Produce hydrogen for captive use by NPPs
- Produce hydrogen for first movers of clean hydrogen; fuel-cell buses, heavy-duty trucks, forklifts, and industrial users



**Exelon will commence testing within 18-24 months at a to-be-announced LWR plant.

LWR-H_2 Demonstration Projects: Davis Besse, Ohio, USA



Electrical Tie-In

Power Block

Hydrogen Production Area

**Commence testing in 24-36 months.

Purpose: *Produce hydrogen for first movers of clean hydrogen; fuel-cell buses, heavy-duty trucks, forklifts, and industrial users*

energy harbor

Xcel Energy

aps

Industry Consortium of Energy Harbor, Xcel Energy, Arizona Public Service, DOE Labs

—

The engineering design team will design and locate the hydrogen production equipment such that the effect on the design and licensing basis is mitigated (to the extent practical).

Analysis Report: Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest

LWRS LIGHT WATER REACTOR SUSTAINABILITY

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Stake Holder Discussion

- Round-the-table input and comments (45 minutes)
  - Summary of owner interests and questions
  - Recommendations for timing and approaches to engage technology providers and industrial partners

energy harbor

Exelon.

Nebraska Public Power District

Xcel Energy℠

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Wolf Creek Nuclear Operating Corporation

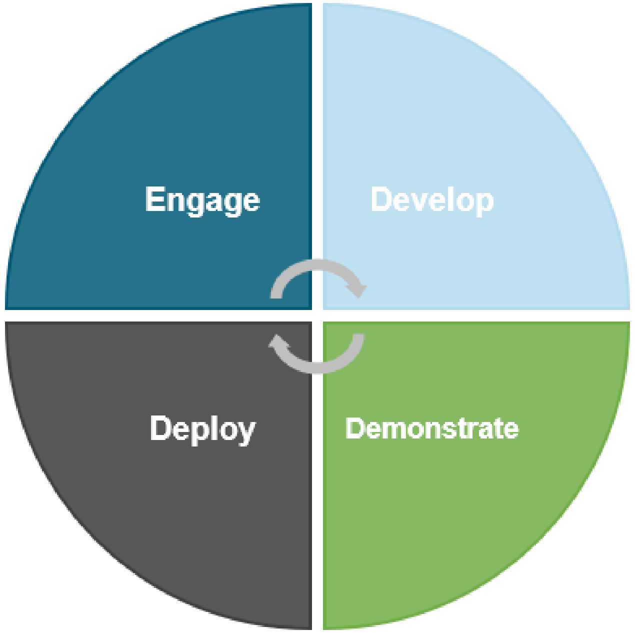
aps

Southern Nuclear

DUKE ENERGY®

Stake Holder Discussion

- Next Steps (15 minutes)
  - Next meeting time, format, and participation
  - Research Leads follow-up with individual stakeholders
  - Arranging meetings with technology and industrial stakeholders
  - Other…

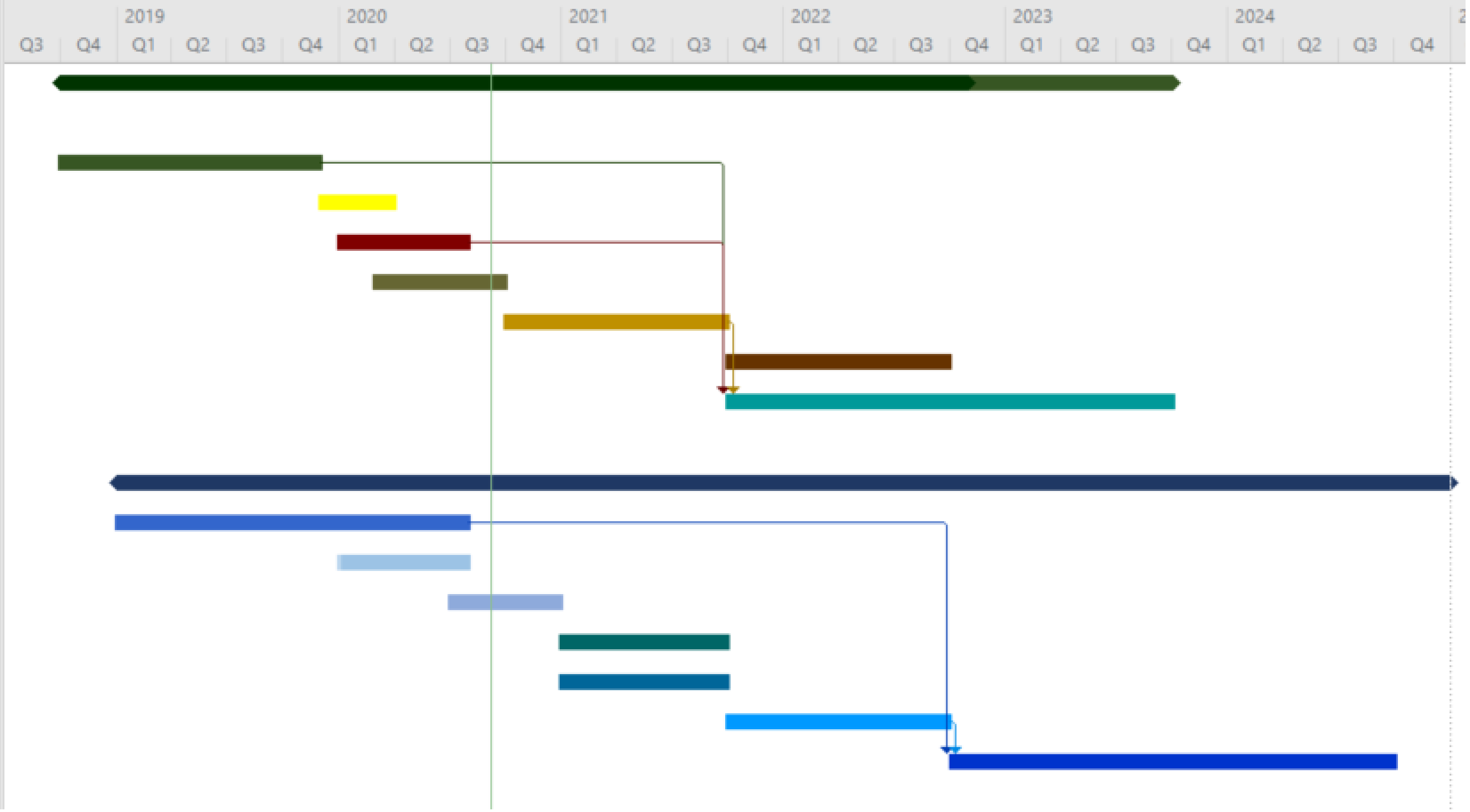


Richard

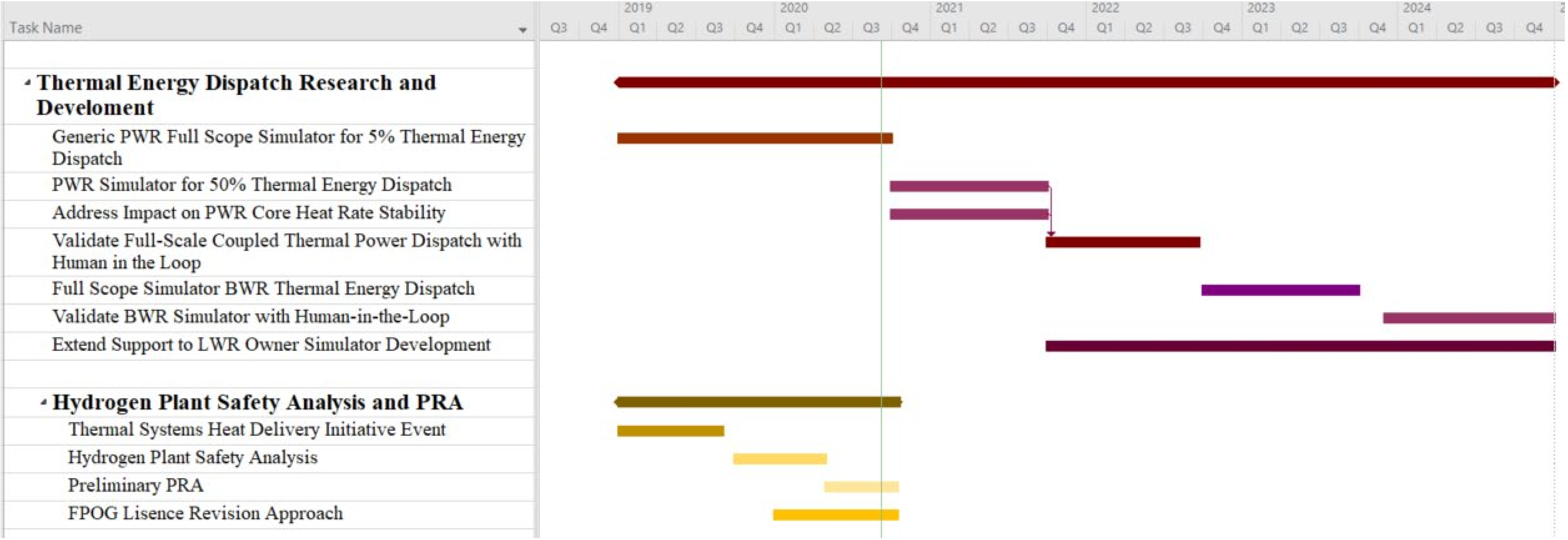
LWRS LIGHT WATER REACTOR SUSTAINABILITY

TEA Program Timeline

Task Name
LWR Process Integration and Plant Design Economics
Hydrogen & H2 Industries Plants
Polymer Plants
Thermal User Industries
Synthetic Fuels Plants
Energy Storage
Refineries
Energy Complexes, Jobs Anlaysis, Life-Cycle Benefits
FPOG Optimization in Regulated and Deregulated Markets
RAVEN / HERON / TEAL Tools Development
Deregulated Electricity Markets
Regulated Electricity Markets
Graphic User Interface with Model Release
New Release with Energy Storage Options
Real Time Optimization with Expanded Data Structure
Validate HERON for Real Time Optimization



Interface Development



- [ ] Summary and adjourn (5 minutes)

LWRS

LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

lwrs.inl.gov

Tyler

Future Work

- **Further development of Full-Scope Generic Simulator (FY2021)**
  - Add coupled electric power dispatch to Full Scope Thermal Power Dispatch GPWR
  - Add high fidelity simulation of industrial user for realistic coupling between PWR and high temperature hydrogen generation plant
  - Repeat human-in-the-loop tests with expanded operations that include maintenance, abnormal, and emergency scenarios
  - Investigate other technical options:
    1. Use steam as the heat transfer media (current simulator uses synthetic oil);
    2. Further automate the controls of the integrated system;
    3. Change industrial use industrial user to ammonia plant or other

- **Develop Full-Scope Plant-Specific Coupled Thermal and Electric Power Dispatch Simulator (FY2021-FY2022)**
  - Identify first mover PWR for simulator development/modifications
  - Add industrial user plant response specific to high temperature hydrogen generation
  - Validate simulator predictions
  - Perform human-in-the-loop tests
  - Make simulator available to address licensing issues and techno-economic questions
  - Address other technical options…

- **Repeat above work with BWR Simulator… (FY2022-FY2023)**